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Analog Computation with Magnetoresistance Multipliers

Novel technique multiplies and divides in same package, achieves up to 0.1% accuracy for total cost less than $350 and provides electrical isolation between input and output signals.

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This article describes a little-known technique for multiplying, dividing and otherwise manipulating AC and DC signals using flux-variable resistors (magnetoresistors) in a novel bridge configuration. The basic magnetoresistance bridge* forms a four-quadrant multiplier, but with the aid of operational amplifiers, provides 0.1% linearity in squaring, square-rooting, modulating, mixing, demodulating, rectifying, and related applications.

One particular version of the unit, which will be described here, develops an output proportional to kAB/C, where A, B, and C are three independent variables. The unit simplifies many mathematical functions by simultaneously multiplying and dividing, and makes a phase-stable modulator, or electrically isolated amplitude control, for precision AC reference voltages.

Particular merits of magnetoresistance multipliers include their natural compatibility with off the shelf operational amplifiers, as well as their simplicity, versatility, and high linearity and temperature-stability when feedback is applied.

In essence, the magnetoresistance multiplier is a solid-state analog of electromechanical multipliers based on servo-driven potentiometers. Naturally, the solid-state unit affords considerably better bandwidth than its electromechanical counterpart; it also costs less, requires less space, is virtually maintenance-free, and operates on a fraction of the power. It also permits 1% accuracy over a 100°C temperature range for less than $350 total parts costs.

Frequencies to 1 MHz can be applied to the multiplier's bridge circuit providing careful capacitive trimming is used, while an upper limit for coil inputs is about 1 kHz. Coil frequency can be extended in special units by use of ferrite cores, or by resonating the coil over specific narrow-band frequency ranges.

MAGNETORESISTANCE

Magnetoresistance is a fundamental phenomenon allied to the Hall effect, and present in many materials, but exhibiting greatest sensitivity in bismuth and such semiconductors as indium arsenide and indium antimonide. Indium antimonide has the highest flux-sensitivity, but present production techniques require 0.02″ thick ceramic substrates and yield only modest zero-flux resistivities. On the other hand, bismuth provides a better overall compromise because thin-film layers can be deposited on 0.002″ mylar substrates to make flexible sandwich elements capable of slipping into 0.005″ air gaps. Optimum resistance levels for bismuth magnetoresistors are around 1000 ohms, with 0.1 watt dissipation.

Typical bismuth magnetoresistors undergo roughly 10% resistance change for 5 kilogauss flux-density variations. Although this might seem a small resistance swing for most uses, careful design of the multiplier's magnetic circuit turns this 10% change into a ±60 dB dynamic signal range. Output level at null is limited by noise, second harmonics, drift, etc., to about 200 microvolts, while the full 10% resistance swing develops roughly ½ volt output from a magnetoresistance bridge excited at 10 volt.

*American Aerospace Controls, Inc. Series MMA 3000 and MMA 3050

Temperature effects are mostly confined by the bridge configuration to sensitivity-loss at high temperature. Open loop multipliers use negative coefficient thermistors for temperature compensation, while double-bridge units virtually eliminate temperature effects by enclosing the bridge within a high gain feedback loop.

MAGNETORESISTANCE VS. HALL

Magnetoresistance elements have several advantages over Hall elements in multiplier and transducer applications. In the first place, it's a pretty rare Hall multiplier that can develop 500 millivolts output. Secondly, the bismuth magnetoresistor's optimum resistance level of 1000 ohms makes it completely compatible with inexpensive off-the-shelf operational amplifiers. (e.g. Analog Devices Model L114A at $35). By contrast, Hall elements often require 500 milliamps drive current at ½ volt or so, which is far from a convenient level.

Further subtle advantages of magnetoresistors are two-terminal rather than four-terminal connections, inherent drift compensation through the balanced bridge configuration, and self-cancelling of induced voltages by opposed connection of magnetoresistance leads.

A disadvantage of the magnetoresistive element is its nonlinearity: resistance increases as the square of applied flux density over normal densities encountered in transducer work. However, this very square-law effect is harnessed by the multiplier's quarter-square principle to achieve a theoretical straight-line transfer function.

OPERATION

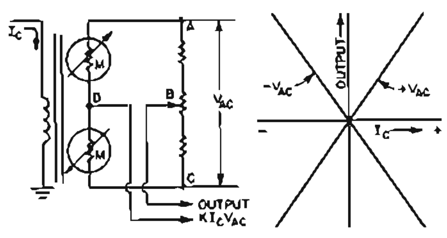


Figure 1. Simplified Multiplier Circuit
Coil input unbalances magnetoresistance bridge, develops output which is product of bridge excitation and bridge unbalance.

A simplified open-loop multiplier is shown in Fig. 1. Inputs are applied to bridge terminals AC and to coil input E. Output, which is proportional to bridge unbalance, is taken from bridge terminals BD. The bridge is unbalanced when the magnetic field set up by coil drive current alters the values of the magnetoresistance bridge arms. The magnetic circuit is arranged so that increased magnetic field increases the resistance of one bridge arm and simultaneously decreases the resistance of the other.

Although output is proportional to bridge unbalance, it is also proportional to the amount of voltage applied across terminals AC. In other words, multiplier output is proportional to the product of bridge unbalance (i.e. current I), and bridge excitation, (V_{AC}).

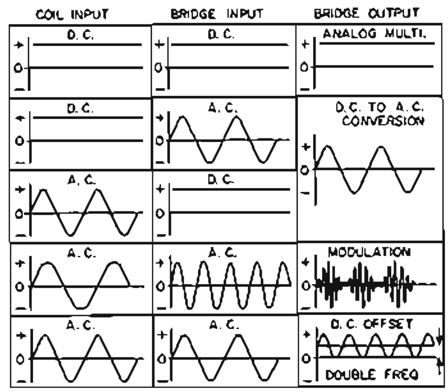


Figure 2. Applications for Multipliers
Waveforms show possible outputs for various combinations of AC and DC inputs.

Four fundamental operations: multiplying, dividing, squaring, and square-rooting can be based on the multiplier as shown in Fig. 3. Here, the multiplier is represented as an ideal "black box," with operational amplifiers forming part of the mathematical functions. In practice, additional operational amplifiers are required to linearize core and bridge characteristics, and also to match input signals to bridge

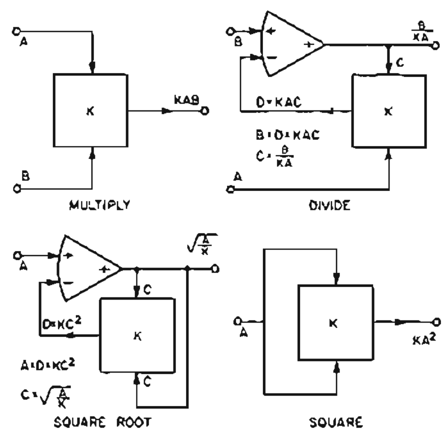


Figure 3. Basic Multiplier Operations
When used with op amps, magnetoresistance bridge impliments four basic operations.

and coil impedances. Modulators, mixers, correlators, demodulators, phase sensitive rectifiers, and many other applications are based on one or another of these basic circuits.

The primary function of the multiplier's magnetic circuit is to produce a linear unbalancing of the bridge in response to one set of input signals. Since the magnetoresistance elements are used in adjacent bridge arms, the magnetic circuit must produce push-pull unbalancing by increasing one magnetoresistor value while decreasing the other.

The magnetoresistor responds to an increase in flux by increasing resistance in a square-law relationship, regardless of the polarity of flux increase. Hence, special trickery is needed to provide polarity-sensitive unbalancing wherein one bridge arm increases resistance while the other decreases, and vice versa.

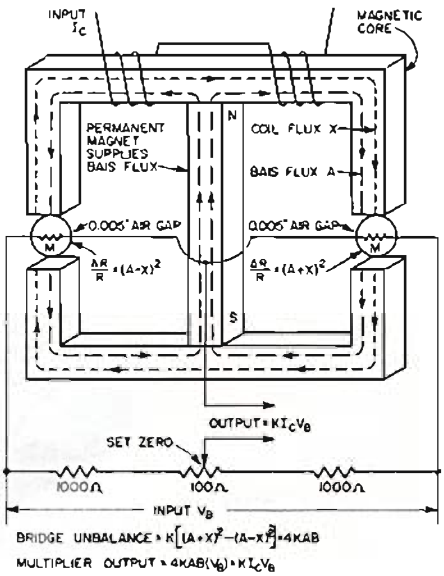


Figure 4. Magnetoresistance Bridge With Permanent Magnetic Bias Coil flux and bias flux added in one air gap, subtract in other to produce push-pull bridge unbalance.

A novel magnetic circuit using permanent-magnet biasing, Fig. 4, solves the problem and linearizes the transfer characteristic in the process. Magnetic flux, X, produced by coil current I, adds to the bias flux A in one air gap, and subtracts from the same value of bias flux in the other. In this way, one magnetoresistance bridge arm increases in value according to the square-law relationship $(A+X)^2$, while the other decreases according to $(A-X)^2$. The net bridge unbalance is proportional to the difference between these changes, hence follows the "quarter-square" relationship $(A+X)^2-(A-X)^2=4AX$. If bias flux is constant (supplied by a permanent magnet), multiplier output is a linear function of flux density, X, hence varies approximately linearly with coil current.

DOUBLE BRIDGE

The previous discussion concludes that the multiplier output varies linearly with coil current. This is only true so long as the multiplier uses magnetic cores with ideal characteristics. Magnetic material like this is pretty hard to come by; so in practice, hysteresis and nonlinearities limit the open loop multiplier's accuracy to about 2%.

Nevertheless, core nonlinearities can be "straightened out" with feedback. Or at least they can be removed from the transfer function by enclosing them in a high gain feedback loop. The actual feedback circuit, Fig. 5, is based on a double bridge multiplier using one bridge for feedback and an identical, closely matched bridge to develop output signals.

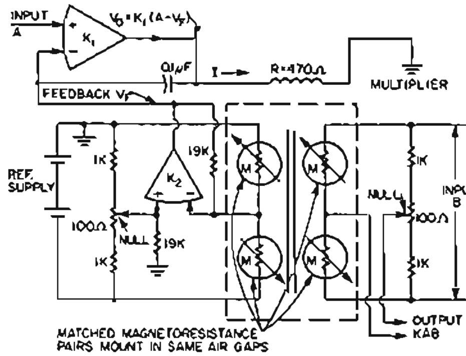


Figure 5. Double Bridge Multiplier for High Accuracy Feedback linearizes magnet and magnetoresistance circuit, unbalances both bridges in response to input A.

So long as the feedback loop remains closed, the left-hand bridge will unbalance in sympathy with input A regardless of core hysteresis or temperature effects in the bridge.

For example: if increased input produces a momentary difference between feedback V_f and input A, the amplifier's high gain will turn this difference $(A-V_f)$ into increased drive voltage for the magnetic coil. The new level of drive voltage, $K_1(A-V_f)$, then increases coil current, hence bridge unbalance, until equality between V_f and A is restored. Actual discrepancy between input and feedback is a few hundred micro-volts, depending upon amplifier gain and DC drift.

This method of feedback controlled bridge unbalancing is used in the double bridge multiplier by making an accurate match between the two magnetoresistance bridge arms sandwiched in each air gap. In this way, feedback controlled unbalance in the left-hand bridge is accurately duplicated by the right hand bridge. Consequently the two bridges track each other with at least 0.1% linearity and 0.01% temperature coefficient for wide ranges of temperature and flux density.

MULTIPLIER-DIVIDER

A versatile analog operational unit based on the double-bridge multiplier is shown with actual component values and operational amplifier types in Fig. 5. Outputs from this multiplier depend upon three independent variables A, B, and C according to the relationship $V_o=kAC/B$. This configuration

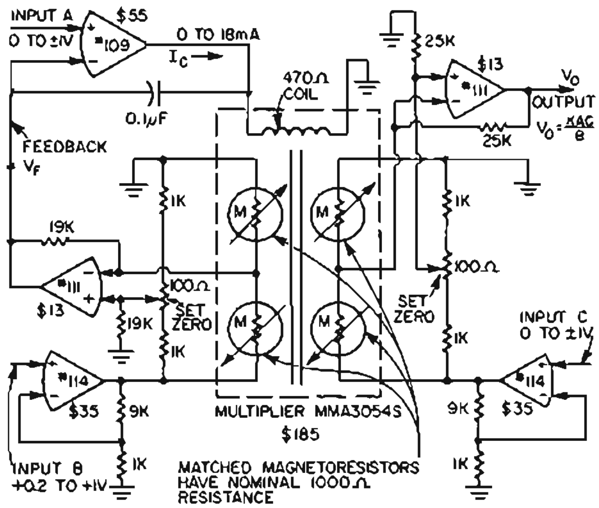


Figure 6. High Accuracy Multiplier — Divider Circuit
Double bridge configuration simultaneously produces four-quadrant multiplication and two-quadrant division. Output is electrically isolated from inputs. Bridge accommodates up to 1 MHz inputs using fast op amps.

works simultaneously as a four-quadrant quarter-square multiplier and a two-quadrant divider, accommodating 0 to ±1V inputs for terminals A and C, and +0.2V to +1V input for terminal B. The output of 500mV or so is amplified to convenient levels by the amplifier K5.

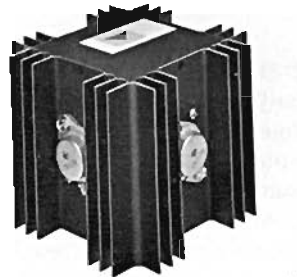
Customers have reported overall accuracies to 0.05% for narrow temperature ranges and using highest stability operational amplifiers. However, for the configuration shown in Fig. 6, with amplifiers totaling less than $160, accuracies to 0.5% for 50°C temperature span are more reasonable. Cost of components for the complete package, with Model MMA3054S listed at $185, is then less than $350.

Simultaneous multiplying and dividing in one analog package is very convenient for handling flow equations, where expressions such as PRESSURE X DIFFERENTIAL PRESSURE÷TEMPERATURE must be manipulated,(Fig. 6). This calculation is performed with one unit, instead of using a separate analog multiplier and a divider which would otherwise be required.

The double bridge multiplier also makes an excellent modulator for controlling an AC carrier with a DC or low frequency input to the coil. (Input B is usually constant) Output from the right-hand bridge is electrically isolated from the coil input and,owing to the bridge's wide bandwidth, permits carrier-frequencies up to 1 MHz to be modulated with very low phase shift.

NEW PRODUCTS

Model 401 Modular Power Amplifier Develops 40 Watt Output From Single +28 Volt Power Supply

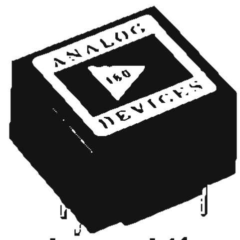


Designed to drive torque motors, deflection coils, M-G sets, servo valves and other high power transducers. Model 401 with fixed gain of 20 is intended to be preceded by a high gain operational amplifier in a wide variety of servo applications. Unique circuitry accepts single ended input signal and delivers a ±20V output swing—all from a single +28V supply.

SPECIFICATIONS

Output Voltage	±20V
Output Current	2 amps
Gain	20V/V
Bandwidth	5kHz
Input Impedance	25K
Temperature Range	−45 to +70°C
Size	3.9"×3.9"×3.2"
Price (1-9)	$275.00

Model 180A/B Chopperless Differential Amplifier with 0.75μV/°C and 1.5μV/°C maximum voltage drift.



Now you can get drift performance of chopper stabilized amplifiers for one half the price and in one third the size. New Model 180 also offers advantages of lower noise, higher input impedance and the versatility of differential inputs. You can build a low level voltage follower with 1000 Megohm input impedance or a differential amplifier with 100db CMRR and 1μV noise.

Unlike most differential amplifiers, special dual input transistor circuit of the 180 is virtually immune to offset errors due to thermal gradients. Warm up drift is typically less than 5μV.

SPECIFICATIONS

Voltage Drift, max.	0.75μV/°C(B) and 1.5μV/°C(A)
Long Term Stability	5μV/day
Bias Current, max.	±2nA @ 25°C
Offset Current Drift	0.01nA/°C
Input Impedance	2MΩ & 1000MΩ
DC Gain	3×10^5
Output Rating	±10V @ 2.5mA
Noise, p-p	(.01 to 1Hz) 1μV & 5pA
Common Mode Rejection	100,000
Price (1-9)	$80. (A), $110. (B)